INVESTIGATION OF CHARGE-RATE INCREASE FOR A CAPACITOR CHARGING POWER SUPPLY IN BURST MODE OPERATION

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Abstract

Interest in rep-rate operation of pulsed power systems has led to an increase in power requirements of high voltage (HV) capacitor charging power supplies (CCPS). Compact repetitive pulse power systems provide an impetus to develop supplies with a high power density (HPD). We have an application requiring compact HPD CCPS's and have evaluated a number of options to determine their applicability to a bipolar charging scheme with a charge rate requirement of 6400 J/s. The load for our application has significantly imbalanced charge rail stray capacitances, which introduces issues with CCPS polarity dominance and no commercially available options were found to be satisfactory. This paper discusses our effort to modify a commercial CCPS to meet our requirements for charge rate and control versatility.

Two Lambda Americas model 152A CCPS, of opposite polarities, were modified to operate from DC prime power and used to charge a bench load capacitance with integrated diagnostics. The primary objective was to double the effective rating of the commercial supply in a low duty cycle burst mode through modification of the operating parameters. The impact of variable switching frequency, passive resonant component value, and prime power voltage level on the charge rate is examined in detail. Burst-mode charge rate increases of greater than three times the continuous rating are reported. The impact on efficiency and reliability of the supply after modifications is also discussed.

I. INTRODUCTION

As pulsed power applications require increased repetition rates, the corresponding power requirements of the power supplies must also increase. Compact repetitive pulse power systems further limit the CCPS options to only those with a HPD. The application of interest requires a compact, DC-driven power supply for repetitive charging of a capacitive load. With inductive isolation of the capacitor bank, the pulse repetition frequency (PRF) is primarily limited by the charge rate of the power supplies. Several options were evaluated to determine their applicability to a bipolar charging scheme comprised of a load capacitance of approximately 100 nF charged to +/- 40 kV at a PRF of 20 Hz, corresponding to a charge rating of 6400 J/s. Imbalanced charge rail stray capacitance further complicate the bipolar charging setup by requiring one polarity to charge a slightly greater load capacitance. A difference in charge rate between the two CCPS creates a dominant rail, which can prevent firing of the load capacitor discharge circuit. Numerous application specific HPD CCPS are currently under development, although none meet all of the system requirements [1,2,3].

The power supply explored in this paper is the Model 152A CCPS produced by Lambda Americas. The 152A is a compact device (6”x6”x14”) that uses a half-bridge, parallel resonant inverter topology to achieve an output of up to 40 kV at 1500 J/s for continuous operation. A pulse-pulse repeatability of +/- 0.2% is possible with the 152A, a requirement for many laser applications that use this type of the supply. However, this extremely high pulse-pulse repeatability is not a requirement for our system. The control circuit that provides the repeatability also impedes operation of a pair of 152A supplies in a series bipolar configuration into an unbalanced load [4]. The primary concern for this HV repetitive application is charge rate, coupled with balanced bipolar charging and moderate efficiency. The goal of the CCPS modification was to increase the effective rating of the commercial supply to greater than 3000 J/s in a low duty cycle burst mode.

Several methods of increasing the charge rate of the resonant CCPS were investigated. Variation of the discrete LC components allowed modification of the resonant impedance and frequency. Development of a new control system provided increased switching frequency range, facilitating improved dominance control and compensation for various prime power levels.

II. CCPS THEORY OF OPERATION

The Lambda Americas 152A is a commercial HV switching power supply designed to provide constant current for rapid capacitor charging. This half bridge Insulated Gate Bipolar Transistor (IGBT) parallel resonant supply is capable of 1500 J/s output up to 40 kV

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14. ABSTRACT
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in a compact package. The supplies are fixed polarity, dictated by the diode configuration in the sealed HV tank. The 152A is designed to typically operate from 115 V, 60 Hz. With guidance from Lambda Americas, several minor modifications were made to a set of positive and negative 152A units that enable them to operate up to 50 kV from DC input ranging from 275-400 V.

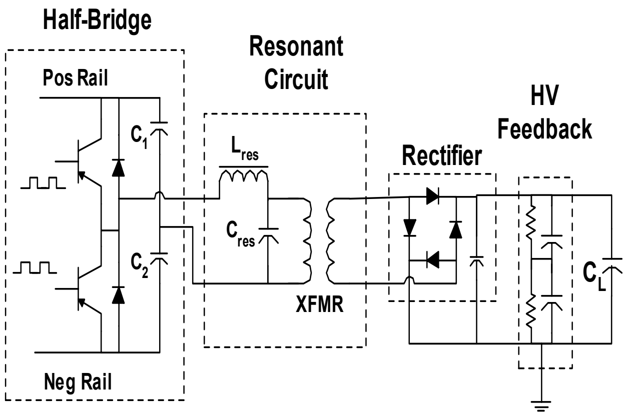

Figure 1. Block diagram of CCPS.

The CCPS consists of the control board, half-bridge, resonant circuit, HV rectifier and HV feedback, as illustrated in Figure 1. Control requirements encompass providing gate drive signals, HV feedback monitoring, enable window, and program voltage comparison. An inverter board contains the IGBT half-bridge, two gate drive circuits and the discrete portion of the resonant circuit. A HV tank houses the transformer, rectifier and voltage divider circuit for HV feedback.

While application specific controls can become quite complex, only a few control signals are required to drive a CCPS. The gate drive signals turn the IGBTs on for alternate cycles with a short dead time between switching cycles to prevent simultaneous conduction of the switches. All other control signals involve the modification or enabling the gate drive. The desired output level is set with a program voltage. An enable window provides a secondary level of output voltage limiting by allowing only a fixed operating period for the power supply. Modifications to the gate drive frequency or duty cycle adjust the CCPS charge rate.

The half-bridge inverter chops the DC prime power into an AC voltage for the transformer input. The HV transformer steps-up the voltage from several hundred volts to tens of kilovolts, which is then rectified to obtain the desired DC HV output. The IGBTs of the half-bridge are switched by a square wave voltage signal with a frequency and duty cycle dictated by the control system. However, the resonant LC tank circuit between the inverter and the transformer primary alters the quasi-square wave shape of the inverter output. The resonant circuit forces the switching waveform to become sinusoidal, reducing the stress on the IGBTs with zero voltage switching (ZVS). The HV full-bridge rectifier converts the induced currents on the transformer secondary to DC, which provides the output to the load capacitor after passing through a voltage divider HV feedback circuit.

The LC tank circuit is comprised of both discrete components and stray inductance and capacitance from the transformer. This method of operation reduces the switching losses of the transformer, but creates variation in the resonant frequency from 50-54 kHz due to differing strays of each transformer. The relationship between the switching frequency and resonant frequency drastically impacts the CCPS output.

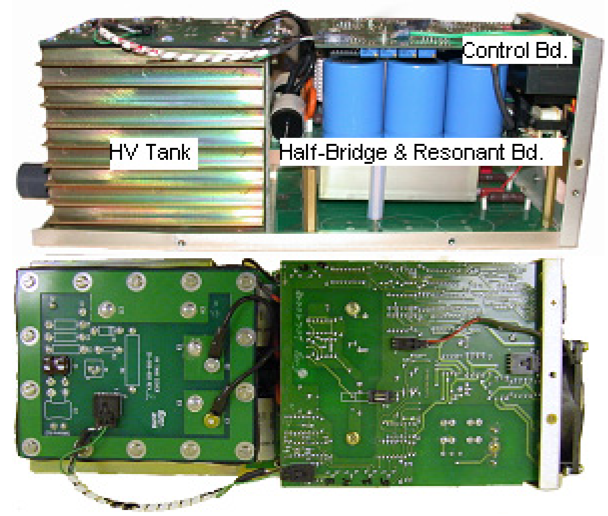

Figure 2. Lambda Americas 152A CCPS.

III. CCPS EVALUATION SETUP

The evaluation system is composed of a pc, control box, fiber optic interface, CCPS and load capacitance. A unique CCPS test stand provides the capacitive load for this evaluation. A 100 nF capacitor bank, a triggering circuit and a high power resistive load allow for rep-rate assessment of the CCPS. Integrated diagnostics provide valuable information regarding charge rate and CCPS operation. Two 20 kW AC-DC supplies or a battery pack provide the DC prime power for testing purposes. The AC-DC supplies are individually capable of 0-600 V, 0-33 A output, but the 33 A limit reduces the actual power available to 11.5 kW per supply at 350 V.

The triggering configuration of the evaluation system creates an increased "stray" capacitive load on the positive rail because of a discrete "doorknob" capacitor. This load difference across the rails is required to ensure proper firing of the spark gap switches. When the trigger pulse is generated, the spark gap switches fire and the stored energy is dumped into the 50-Ω load rated at 300 J/pulse through a 500 nH air-core inductor. Test points from the capacitor bank center point and ground were brought to the cart top to allow easy variation between a balanced, grounded center-point, and unbalanced load. Two HV probes allow verification of the charging outside of the CCPS HV feedback. The test setup also provides for monitoring of the input power, gate drive signals and switching voltage and current.

In order to preserve the high pulse-pulse repeatability, Lambda Americas employs feed-forward control. Using a pair of 152A supplies modified to operate from battery with inherent voltage droop to charge an unbalanced load capacitance significantly alters the control requirements. The new control system moves most of the functionality from the CCPS to the control software, increasing the control versatility and decreasing the required hardware. A new HV feedback box was developed to transmit the signal back to the control software for program voltage comparison via fiber optics. Software additions could permit the controls to vary the switching frequency during the charge cycle to actively modify the charging profile. While this control technique is a significant departure from the original 152A design, it is better suited for this application.

IV. EXPERIMENTAL RESULTS

Four CCPS modifications were examined to determine their impact on charge rate, defined as energy output divided by rep-rate period. The new control set allowed for increased switching frequency range from the original 152A. Variation of the discrete capacitance and inductance of the resonant circuit allowed experimentation with new resonant frequencies and impedances. An inductance reduction by one-quarter was evaluated, as were combinations of LC to create a reduction in only the resonant impedance by one-half and a doubled resonant frequency with a decrease in impedance. Figure 3 displays charging waveforms from several modifications. The power supply charge rate is not only a function of modification, but also input voltage and switching frequency. To simplify modification comparison, all four techniques were examined using a single positive HV tank. As illustrated in Figure 4, the charge rate increases at switching frequencies below resonance for all modifications. The resonant frequency and impedance modification produced the highest charge rate of greater than 5 kJ/s at 45 kHz with an input voltage of 350V.

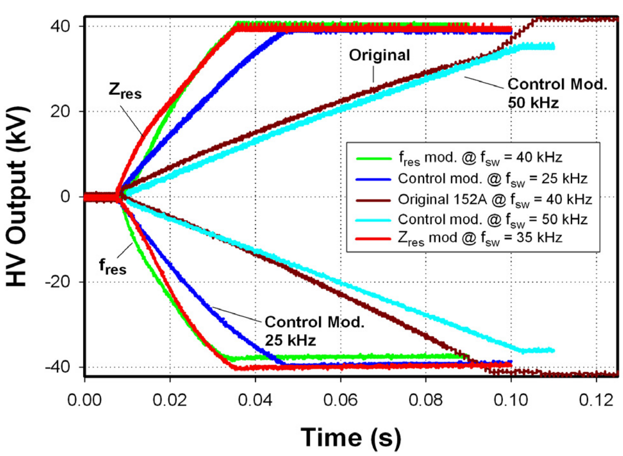

Figure 3. Bipolar HV charge comparison at Vin = 325 V

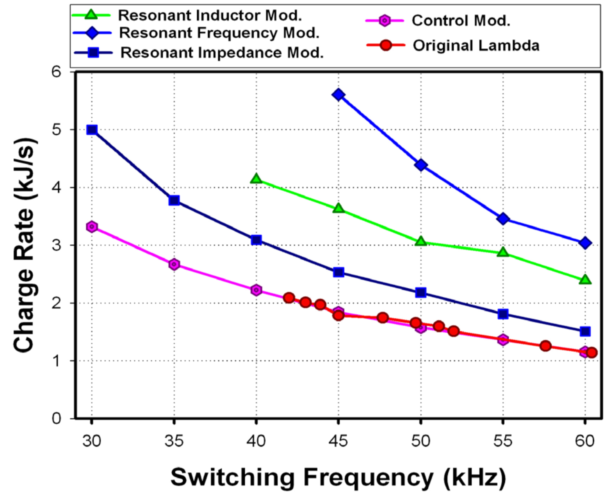

Figure 4. Charge rate vs. frequency comparison @ 350V

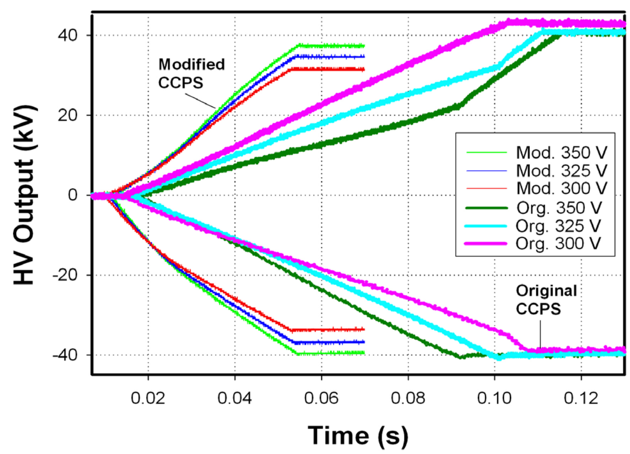

Figure 5. Input voltage effects on polarity dominance of the original and modified Lambda 152A power supplies

The application requires not only a higher charge rate, but also a balanced charge voltage on each rail. Prime power provided by single or multiple battery packs creates the possibility of varying DC input voltages to the HV power supplies. The input voltage level was varied from 300-350 V for pairs of original and control modified 152A supplies. With the original 152A a 20% overall charge rate difference was observed with a 50 V input voltage change, as shown in Figure 5. In addition to the overall charge rate difference there is a variation in polarity dominance, with the NEG supply dominant at 300 V and the POS supply becoming dominant at 350 V. This dependency is unacceptable for the application of interest. The control modification uses a constant frequency drive, removing the dependence upon the input voltage. Although a slight drop in charge rate is apparent at lower input voltages with the control modification, the dominance is consistent across a range of input voltages. Active control software could provide charge rate compensation for input voltage droop while maintaining a balanced charge and constant dominance. The initial investigation into active control has yielded promising results.

Higher charge rate increases the input power and switching current requirement of the CCPS. This impacts the efficiency and reliability of the supply. As illustrated in Figure 6, the majority of the CCPS efficiencies fell between 80-90%. With the exception of the efficiency near resonance, the efficiencies were relatively unchanged for each modification at various switching frequencies and corresponding charge rates. Upon initial examination, the reliability displays minimal impact from the modifications. However, a more detailed investigation with more data points is required to determine the most reliable modification.

Charge rate increase by any method is limited by IGBT current capability and the saturation point of the ferrite core HV transformer. Both of these potential problems require consideration when modifying a CCPS. IGBT current switching waveforms for various modifications are shown in Figure 7. Switching current increases proportional to the charge rate, with a maximum of near 75 A for a 4.38 kJ/s charge rate. The waveform of the switching current does not change as the charge rate increases. Several of the modifications explored provided sufficient charge rate increase to reach the desired PRF. Operation of a pair of CCPS at 20 Hz is illustrated in Figure 9.

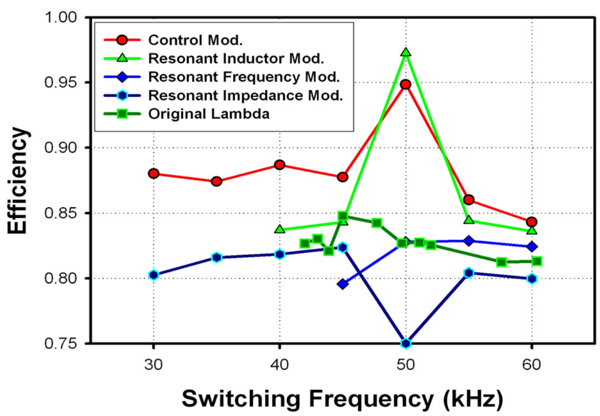

Figure 6. Efficiency comparison against switching frequency for various modifications at Vin=350 VDC.

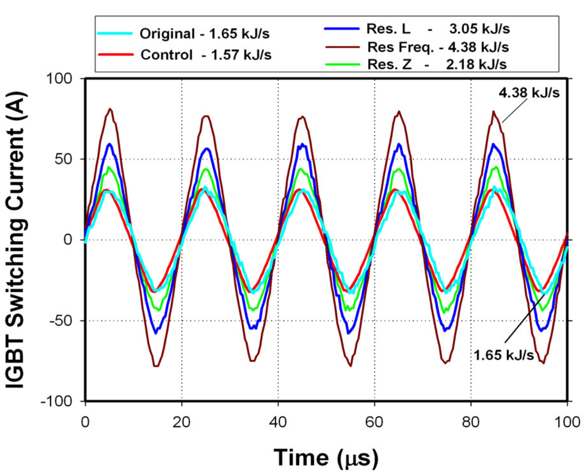

Figure 7. Comparison of current through IGBTs at a switching frequency of 50 kHz with Vin=350 VDC.

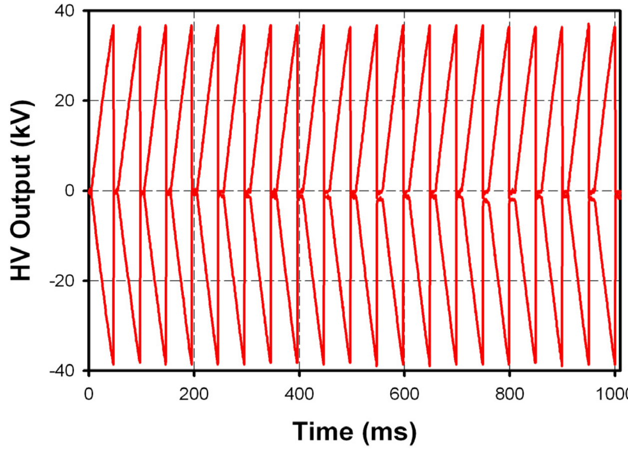

Figure 9. Rep-rate burst of 20 shots @ 20 Hz.

V. CONCLUSION

Modification of the CCPS resonant frequency, resonant impedance and switching frequency range led to charge rate increases over three times the advertised value, with a limited impact on efficiency and reliability. A new control system was developed to provide more flexibility and control of bipolar charging. With more than triple the original charge rate from the modified CCPS, a PRF of 20 Hz was successfully demonstrated.

Future work will investigate additional techniques for CCPS charge rate improvement. Additional combinations of discrete resonant LC components could potentially further the increases described. A comparison of alternate converter topologies could also provide an increased charge rate. Completion of active control development should provide additional control of the charge profile. Further investigation of power supply reliability and efficiency required for determining optimal modification.

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